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***B*-mode contamination by synchrotron emission from 3-yr *Wilkinson Microwave Anisotropy Probe* data**

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ABSTRACT

We study the contamination of the *B*-mode of the cosmic microwave background polarization (CMBP) by Galactic synchrotron in the lowest emission regions of the sky. The 22.8-GHz polarization map of the 3-yr *Wilkinson Microwave Anisotropy Probe* (WMAP) data release is used to identify and analyse such regions. Two areas are selected with signal-to-noise ratio $S/N < 2$ and $S/N < 3$, covering ~ 16 and ~ 26 per cent fraction of the sky, respectively. The polarization power spectra of these two areas are dominated by the sky signal on large angular scales (multipoles $\ell < 15$), while the noise prevails on degree scales. Angular extrapolations show that the synchrotron emission competes with the CMBP *B*-mode signal for tensor-to-scalar perturbation power ratio $T/S = 10^{-3}$ – 10^{-2} at 70 GHz in the 16 per cent lowest emission sky ($S/N < 2$ area). These values worsen by a factor ~ 5 in the $S/N < 3$ region. The novelty is that our estimates regard the whole lowest emission regions and outline a contamination better than that of the whole high Galactic latitude sky found by the WMAP team ($T/S > 0.3$). Such regions allow $T/S \sim 10^{-3}$ to be measured directly which approximately corresponds to the limit imposed by using a sky coverage of 15 per cent. This opens interesting perspectives on the investigation of the inflationary model space in lowest emission regions.

Key words: polarization – radiation mechanisms: non-thermal – cosmic microwave background – diffuse radiation – radio continuum: ISM.

1 INTRODUCTION

The cosmic microwave background polarization (CMBP) allows the study of the first stages of the Universe and is one of the hot topics of cosmology. One of its components, the *B*-mode, is sensitive to the primordial gravitational wave (GW) background left by inflation giving a way to investigate the physics of the very early Universe (e.g. Kamionkowski & Kosowsky 1998). In fact, its power spectrum on degree scales has a linear dependence on the tensor-to-scalar perturbation power ratio T/S , which measures the amount of primordial GW (e.g. Boyle, Steinhardt & Turok 2006; Kinney et al. 2006). In combination with parameters measured by the CMB temperature spectrum (the scalar perturbation spectral index n and its running $dn/d \ln k$), it allows us to distinguish among the numerous models of inflation.

The *B*-mode signal is faint and only upper limits of T/S have been set so far. Seljak, Slosar & McDonald (2006) and Martin & Ringeval (2006), using different analyses, find consistent results of $T/S < 0.22$ and $T/S < 0.21$ (95 per cent confidence level),

respectively. On the other hand, the plethora of inflation models does not help constrain T/S . This can vary by orders of magnitude and can be even smaller than 10^{-4} , although Boyle et al. (2006) show that only models with high fine tuning degree can feature $T/S < 10^{-3}$. Correspondingly, the peak *B*-mode signal can vary from ~ 200 nK of the present upper limits down to values even smaller than 3 nK for $T/S < 10^{-4}$.

The weakness of the CMB *B*-mode makes it easily contaminated by foreground emissions from both the Galaxy and extragalactic sources. The study of astrophysical foregrounds is thus crucial to set the capability of CMBP experiments to investigate the early Universe and help set which part of the inflationary model space is accessible.

At frequencies lower than 60–70 GHz, the most relevant contaminant is expected to be the Galactic synchrotron emission. Recent results based on 3-yr *Wilkinson Microwave Anisotropy Probe* (WMAP) data at 22.8 GHz show that even the high Galactic latitudes are normally strongly contaminated (Page et al. 2006). These authors use about 75 per cent of the sky (all high latitudes but strong large local structures like the Northern Galactic Spur) and find that at 60–70 GHz the synchrotron emission competes with the cosmic *B*-mode signal even for models with $T/S = 0.3$ – 0.5 , which are

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already disfavoured by the present upper limits. Similar results are obtained by La Porta et al. (2006) through the analysis of the 1.4-GHz sky at latitude $|b| > 20^\circ$ using the Dominion Radio Astrophysical Observatory (DRAO) survey data (Wolleben et al. 2006).

La Porta et al. (2006) also analyse areas¹ with smaller extension (for a total of about 10 per cent of the sky) and lower emission, finding that the Galactic signal at 70 GHz is comparable to the CMB B -mode in the case of $T/S \sim 0.1$. Even though it is lower, this signal would largely contaminate the CMB B -mode for most of the T/S values presently allowed. However, these areas are not in the lowest emission regions visible in the 22.8-GHz *WMAP* polarization map.

Information about the lowest emission regions are available, instead, from three independent small areas observed at 1.4 and 2.3 GHz (Carretti et al. 2005b, 2006; Bernardi et al. 2006). The synchrotron emission here actually looks weaker, competing with the CMB B -mode only for cosmological models with $T/S = 10^{-3}$ – 10^{-2} at 70 GHz (Carretti et al. 2006).

Such values would give more chances to investigate a large part of the inflationary model space, opening interesting perspectives for the study of the inflation physics. However, the areas observed so far cover just few square degrees (~ 20 deg² in total) and represent few sparse samples of the lowest emission regions. A real knowledge of the typical Galactic synchrotron contribution of such regions is still an open question, and requires wider areas to be analysed.

This Letter reports the first study carried out to identify and analyse the areas with the lowest synchrotron emission at microwave wavelengths, which allow negligible Faraday rotation effects (still appreciable at ~ 1 GHz; e.g. see Carretti et al. 2005a). We use the 22.8-GHz polarization map of the 3-yr *WMAP* data release to select them (Section 2), and compute their polarized angular power spectra (Section 3). Finally, we estimate the contamination of the CMBP by Galactic synchrotron in the CMBP frequency window (70–90 GHz) and discuss implications for the detection of the cosmic B -mode in lowest emission regions (Section 4).

2 LOWEST EMISSION REGIONS SELECTION

The 3-yr *WMAP* data release² has made available the first polarization all-sky map at microwave frequencies, namely 22.8 GHz (Page et al. 2006). The sensitivity does not allow to detect the signal out of the Galactic plane at the nominal resolution (full width at half maximum, FWHM, $\sim 1^\circ$). The high Galactic latitudes have low signal-to-noise ratios (S/N), except in large local structures such as the big supernova remnant (SNR) loops. The situation improves once data are averaged on pixels of $\sim 4^\circ$ (top panel of Fig. 1), as presented by the *WMAP* team (Page et al. 2006). At this resolution the signal appears even at high Galactic latitudes and allows us to identify the lowest emission regions in the sky (blue areas in top panel of Fig. 1), which, however, still have signal competing with the noise.

We quantitatively select the lowest emission regions using the 4° polarized intensity map. After accounting for the noise bias (Uyaniker & Landecker 2002), pixels with S/N smaller than a given threshold have been selected. Namely, we have considered two val-

¹ Three areas defined as follows: (A) $180^\circ < l < 276^\circ$, $b > 45^\circ$; (B) $193^\circ < l < 228^\circ$, $b < -45^\circ$; (C) $65^\circ < l < 180^\circ$, $b > 45^\circ$; l and b are Galactic longitude and latitude, respectively.

² <http://lambda.gsfc.nasa.gov/>

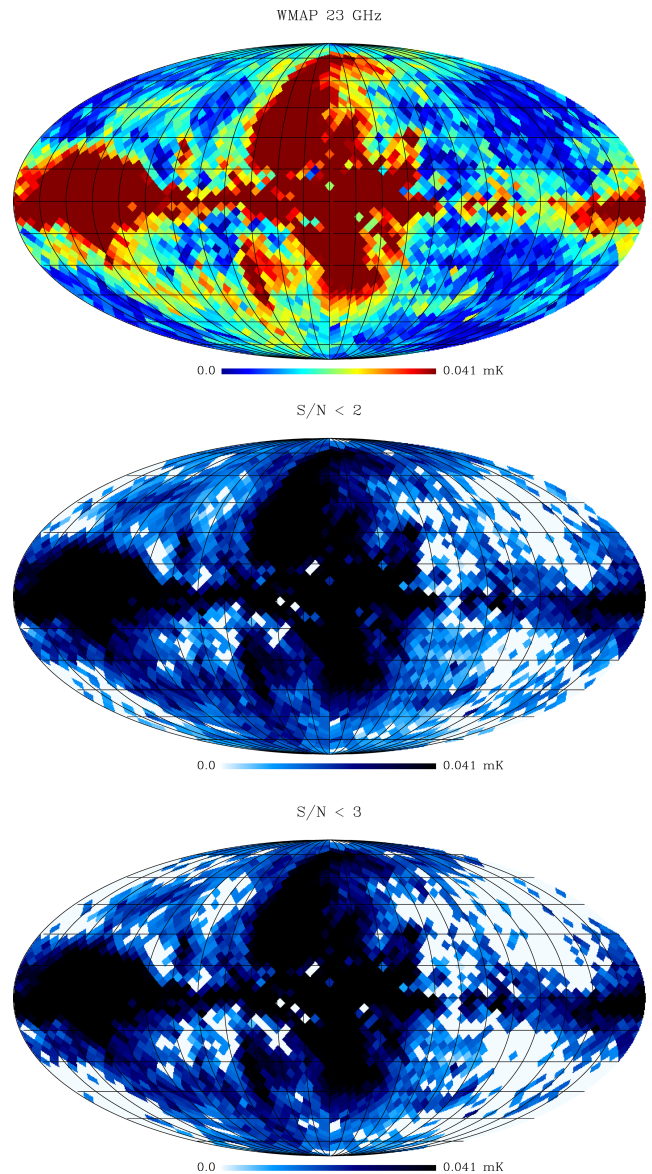


Figure 1. Top. Polarized intensity map at 22.8 GHz of the *WMAP* experiment (Page et al. 2006). Data are averaged on a $\sim 4^\circ$ scale using the HEALPIX (Górski et al. 2005) pixelation with parameter $N_{\text{side}} = 16$ (resolution r4). The map is in Galactic coordinates with the Galactic Centre in the middle. The coordinate grid is spaced in 15° segments both in longitude and latitude. Lowest emission regions are the blue spots at mid-high Galactic latitudes out of the large SNR loops. Middle and bottom. Lowest emission regions in the 22.8-GHz *WMAP* polarization map: the 4° -pixels of the two regions with $S/N < 2$ (middle) and $S/N < 3$ (bottom) are blanked (white).

ues: $S/N < 2$ and $S/N < 3$. The two resulting regions are shown in Fig. 1.

These regions are not contiguous and located at mid-high Galactic latitudes, mainly in the third Galactic quadrant, with significant extensions into the second one. It is worth noting that the Galactic caps are not included, having emission that is too high.

The sky fractions covered are 16.2 per cent ($S/N < 2$) and 25.7 per cent ($S/N < 3$), respectively. Although smaller than half a sky, these two regions have significant extensions and could still effectively be used for CMBP B -mode studies.

3 POWER SPECTRUM ANALYSIS

We compute the *E*- and *B*-mode power spectra of the polarized emission in the two selected areas. These are the quantities predicted by cosmological models and allow a direct comparison with the CMBP signal.

To account for the irregular sky coverage we use the method based on two-point correlation functions of the Stokes parameters *Q* and *U* described by Sbarra et al. (2003). Correlation functions are estimated on the *Q* and *U* maps of the selected regions as

$$\tilde{C}^X(\theta) = X_i X_j \quad X = Q, U \quad (1)$$

where X_i is the pixel *i* content of map *X*, *i* and *j* identify pixel pairs at distance θ . Data are binned with pixel-size resolution. Power spectra $C_\ell^{E,B}$ are obtained by integration

$$C_\ell^E + C_\ell^{E,n} = W_\ell \int_0^\pi [\tilde{C}^Q(\theta) F_{1,\ell 2}(\theta) + \tilde{C}^U(\theta) F_{2,\ell 2}(\theta)] \sin(\theta) d\theta \quad (2)$$

$$C_\ell^B + C_\ell^{B,n} = W_\ell \int_0^\pi [\tilde{C}^U(\theta) F_{1,\ell 2}(\theta) + \tilde{C}^Q(\theta) F_{2,\ell 2}(\theta)] \sin(\theta) d\theta, \quad (3)$$

where the functions $F_{1,\ell m}$ and $F_{2,\ell m}$ are described by Zaldarriaga (1998), $C_\ell^{E,n}$ and $C_\ell^{B,n}$ are the noise spectra, and W_ℓ is the pixel window function accounting for pixel smearing effects. The *WMAP* map smoothed on 1° pixels (HEALPIX parameter $N_{\text{side}} = 64$) has been used to compute correlation functions and spectra, instead of the 4° one used for the selection. This allows us to reduce the effects of the pixel window function and provides reliable computation up to $\ell \sim 100$ of the *B*-mode peak.

Fig. 2 shows *B*-mode spectra in the two selected areas. These are steep on large angular scales, with the $S/N < 2$ case having less power than $S/N < 3$, as expected according to selection criteria. A flattening instead occurs on small angular scales. This behaviour indicates that the signal prevails on large scales ($\ell < 10$ and $\ell < 15$ for $S/N = 2$ and 3, respectively), while the noise dominates on the smallest ones. To check if the flat component is compatible with noise, we performed Monte Carlo simulations. We have generated 100 noise map realizations using the sensitivity map provided in the *WMAP* data package. Then we compute their spectra using only the pixels of the two selected regions. For both cases, we find that the

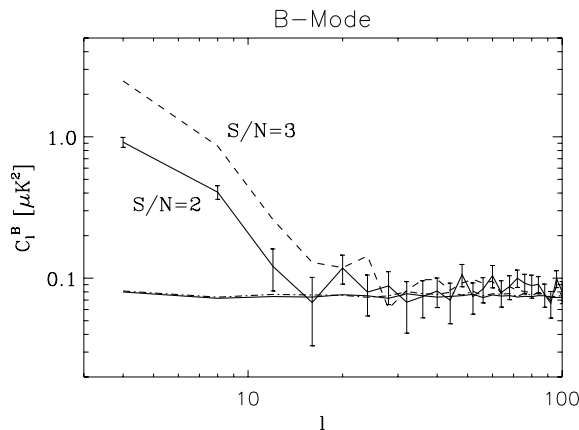


Figure 2. *B*-mode spectra of the *WMAP* 22.8-GHz polarization map in the two regions with $S/N < 2$ (solid line) and $S/N < 3$ (dashed line). To avoid confusion, error bars are reported for the $S/N < 2$ case only. The mean noise spectra of the Monte Carlo simulations are also reported (dot-dashed and triple-dot-dashed for $S/N < 2$ and $S/N < 3$, respectively).

Table 1. Mean value of $\langle \ell(\ell+1)/(2\pi)C_\ell^B \rangle$ – see text. Fit parameters of *B*-mode spectra for $S/N < 3$ are also reported. The ℓ -range used for the estimates is indicated.

S/N	ℓ -range	$A_{10}^B [\mu K^2]$	β^B	$\langle \frac{\ell(\ell+1)}{2\pi} C_\ell^B \rangle [\mu K^2]$
2	[4, 12]			2.8 ± 0.3
3	[4, 24]	0.30 ± 0.06	-2.4 ± 0.3	7.62 ± 0.14

average spectrum is flat with normalization $C_\ell^B = 7.5 \times 10^{-2} \mu K^2$ and $7.3 \times 10^{-2} \mu K^2$ for $S/N < 2$ and $S/N < 3$, respectively, which are compatible with the level of our spectra at large ℓ (Fig. 2). In addition, the spectra of the two S/N cases converge to the same value in the flat range, which again suggests the spectra are noise dominated there. We use the mean noise spectra attained with the Monte Carlo simulations to account for the noise bias in all the next evaluations.

We tried to fit a power law

$$C_\ell^B = A_{10}^B \left(\frac{\ell}{10} \right)^{\beta^B} \quad (4)$$

to the spectra. Only the case $S/N < 3$ allows meaningful results (Table 1), because only few points (three) can be effectively used for $S/N < 2$, after the noise bias is subtracted for. To provide an estimate of the mean emission also for the $S/N < 2$ case, we compute the mean value of the quantity $\ell(\ell+1)/(2\pi) C_\ell^B$ over the usable ℓ -range, which is $\ell \leq 12$. The result is reported in Table 1, along with the same estimate for the $S/N < 3$ area. It is worth noting that there is a factor ~ 3 in spectrum ($\sim \sqrt{3}$ in signal) between the mean emissions of the two analysed regions. Moreover, the emission we found in the $S/N < 2$ region is a factor ~ 10 weaker than that measured in the ~ 75 per cent sky fraction in the same ℓ -range (Page et al. 2006).

4 IMPLICATION FOR CMBP *B*-MODE AND DISCUSSION

The contamination of the CMB *B*-mode signal can be estimated by extrapolating the spectra of Section 3 to 70 GHz, a frequency in the range where the combined contribution of synchrotron and dust is believed to be minimum (Page et al. 2006; Carretti et al. 2006). It is worth noting that typical values of rotation measure at high Galactic latitudes ($RM \sim 10\text{--}20 \text{ rad m}^{-2}$) generate polarization angle rotations of 6–12 arcmin at 22.8 GHz. Thus, Faraday rotation effects can be considered negligible, allowing safe frequency extrapolations.

Our spectra are noise-dominated at the multipole $\ell \sim 90$ at which the CMB *B*-mode peaks, so that direct extrapolations of the measured spectra would provide just upper limits. Then, we adopt another approach: we use the spectra measured in the ℓ -range where they are signal-dominated and perform angular extrapolations to the scale of interest. The mean emission is that provided by the last column of Table 1. As for the extrapolation, the analysis of the 1.4-GHz DRAO survey data shows that the angular behaviour of Galactic synchrotron spectra is well represented by a power law

$$C_\ell \propto \ell^\beta \quad (5)$$

with slope β varying in the range $[-2.5, -3.0]$ for $\ell = 2\text{--}300$ (La Porta et al. 2006; Burigana et al. 2006). This is consistent with the value of $\beta = -2.6$ quoted by the *WMAP* team for the whole 75 per cent of the sky they consider (Page et al. 2006). We use as slope both edge values of the β range (-2.5 and -3.0) and start

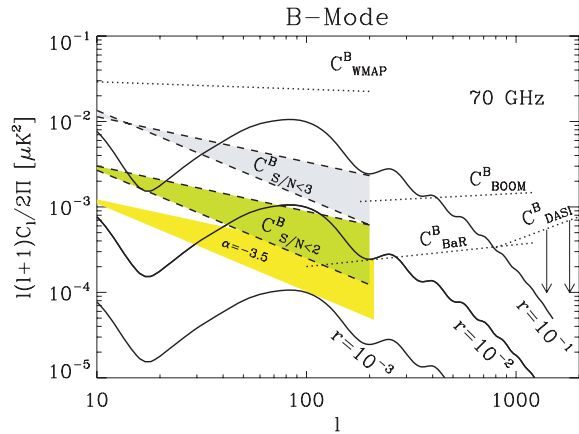


Figure 3. *B*-mode power spectra of the Galactic synchrotron emission estimated at 70 GHz in the regions with $S/N < 2$ (green shaded area) and $S/N < 3$ (grey shaded area). The two angular extrapolations with $\beta = -2.5$ and -3.0 are reported (upper and lower dashed line of shaded areas). A slope $\alpha = -3.1$ is assumed for the frequency extrapolation. The case of a slope $\alpha = -3.5$ is also reported for the $S/N < 2$ region (yellow shaded). For comparison, the plot shows CMB spectra for three different values of $r = T/S$, the synchrotron emission detected in the two low emission areas in the target fields of the *BOOMERanG* (C_{BOOM}^B , Carretti et al. 2005b) and *BaR-SPOrt* experiments (C_{BaR}^B , Carretti et al. 2006), and the upper limit found in the DASI fields (C_{DASI}^B , Bernardi et al. 2006). Finally, the general contamination at high Galactic latitude, as estimated by the *WMAP* team using 74.3 per cent of the sky, is also reported: the spectrum at 22.8 GHz is considered (Page et al. 2006) and extrapolated to 70 GHz.

extrapolations from the middle of the ℓ -range used to evaluate the mean spectrum, namely $\ell_0 = 8, 14$ for $S/N < 2, < 3$, respectively.

Frequency extrapolations are performed assuming the brightness temperature of the Galactic synchrotron follows a power law $T_b^{\text{synch}} \propto \nu^\alpha$, with $\alpha = -3.1$ (Bernardi et al. 2004).

Results are reported in Fig. 3. For the $S/N < 2$ case, which concerns ~ 16 per cent of the sky, the contamination range covered by the two angular extrapolations at $\ell \sim 90$ competes with the CMBP *B*-mode for models with $T/S = [3 \times 10^{-3}, 1 \times 10^{-2}]$. The comparison with previous measurements shows these values are significantly lower than the mean contamination estimated by the *WMAP* team for most of the high Galactic latitudes. On the other hand, our results are similar to the contamination estimated in the small sky patches observed in low emission regions (Carretti et al. 2006 and references therein), giving a valuable consistency of results in regions selected with similar criteria (areas in lowest emission regions). Although with the uncertainties of an angular scale extrapolation, our results extend to the whole lowest emission regions the promising indications obtained in those few small sample areas covering just a few square degrees, and strongly support the possibilities to access small T/S values in the lowest emission part of the sky.

The use of frequency slope $\alpha = -3.1$ can be considered as a conservative approach. In fact, Hinshaw et al. (2006) fitted the behaviour of the synchrotron total intensity, finding out a steepening of the slope at the highest frequencies of the *WMAP* range. In particular, they fit $\alpha = -3.5$ in the range 23–60 GHz. With such a slope the synchrotron contamination at 70 GHz further reduces by a factor of 2.5 with respect to $\alpha = -3.1$ and even $T/S \sim [1 \times 10^{-3}, 3 \times 10^{-3}]$ becomes accessible (yellow shaded area of Fig. 3).

The situation is slightly worse for $S/N < 3$, as expected, as higher emission pixels are included in the analysis. However, $T/S = [2 \times 10^{-2}, 4 \times 10^{-2}]$ appears to be still accessible even in this larger

region, assuming $\alpha = -3.1$. These are values better than that for all the high Galactic latitudes (*WMAP* results on ~ 75 per cent of the sky), or in the areas analysed by La Porta et al. (2006).

For the lowest emission areas, the minimum combined synchrotron-dust contamination has been found to be somewhere between 70 and 90 GHz (Carretti et al. 2006). It is thus worthy estimating the synchrotron contamination of our best case ($S/N < 2$) even at 90 GHz. A further factor ~ 4 is gained with respect to 70 GHz (in thermodynamic temperature), and the Galactic signal competes with models with $T/S \sim [1 \times 10^{-3}, 3 \times 10^{-3}]$.

Despite the significant general contamination of high Galactic latitudes, the results obtained by our analysis depict a situation with better and interesting conditions in the lowest emission regions. The possibility to reach T/S values as low as 10^{-3} – 10^{-2} looks to be now extended from few small good sky patches to an area representing ~ 16 per cent of the sky, which could be the right place for deep CMBP observations looking at the *B*-mode.

Limiting observations in small regions, however, imposes intrinsic constraints on the minimum detectable T/S , mainly because of the leakage from *E*- into the weaker *B*-mode. In fact, Amarie, Hirata & Seljak (2005) find that an all-sky survey would allow a detection of T/S with a theoretical sensitivity limit of $\Delta(T/S) = 1.5 \times 10^{-5}$, which becomes $\Delta(T/S) = 3.2 \times 10^{-5}$ when 70 per cent of the sky is available, and $\Delta(T/S) = 10^{-3}$ for 15 per cent (3σ confidence level). It is worth noting that the class of inflationary models with minimal fine-tuning have T/S values ranging between 10^{-3} and 10^{-1} (Boyle et al. 2006), for which a 15 per cent sky portion would be large enough for the first detection of the tensor CMBP component.

In spite of these limitations, the minimum T/S value detectable in 15 per cent of the sky almost matches the limit imposed by the foregrounds we have found in lowest emission regions. Although there are still uncertainties due to the angular extrapolations we need to apply, the search for the *B*-mode in a sky portion of such a size could thus be a good trade-off between intrinsic and foregrounds limits.

In addition, the weakness of the *B*-mode signal already makes it challenging to detect the signal for $T/S = 0.1$ with the present technology (e.g. Cortiglioni & Carretti 2006). It is likely that significant technological improvements will be necessary before cosmologists can carry out an all-sky mapping mission with a sensitivity able to match the intrinsic limit of $\Delta(T/S) \sim 10^{-5}$. Therefore, an experiment aiming at detecting the *B*-mode in a smaller region (10–15 per cent of the sky) can be a valuable intermediate step that would allow us to probe inflation models down to $T/S = 10^{-3}$.

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